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14. ABSTRACT
In collaboration with MIT-LL, UCB intensively studied superconducting flux qubits with two important modifications. The first is the addition of a capacitor across one or more of the junctions (C-shunt), thus ensuring that most of the electromagnetic energy is stored in this capacitor, potentially increasing T1. The second is a reduction of the critical current density of the junctions, reducing the sensitivity to flux noise and increasing T2. With a C-shunt across only the smallest junction, these modifications increased T1 to values as high as 30 us on degeneracy and 90 us away from degeneracy and T2 to values as high as 25 us. We have developed a new

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Report Title

Reduction of Decoherence in the Flux Qubit

ABSTRACT

In collaboration with MIT-LL, UCB intensively studied superconducting flux qubits with two important modifications. The first is the addition of a capacitor across one or more of the junctions (C-shunt), thus ensuring that most of the electromagnetic energy is stored in this capacitor, potentially increasing T1. The second is a reduction of the critical current density of the junctions, reducing the sensitivity to flux noise and increasing T2. With a C-shunt across only the smallest junction, these modifications increased T1 to values as high as 30 us on degeneracy and 90 us away from degeneracy and T2 to values as high as 25 us. We have developed a new technique for phase matching the four-wave mixing process in the traveling wave parametric amplifier (TWPA) called resonant phase matching. By adding shunt resonators to the unit cell of the TWPA, the dispersion relation is modified near the resonance to correct the phase mismatch intrinsic to the nonlinear process. We have observed the effect of correcting the phase mismatch in a preliminary device, which achieved over 20 dB of gain with a full bandwidth of about 3 GHz. Noise measurements of the device show performance within a factor of 3 of the quantum limit.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received   Paper

08/01/2012 13.00 Juha Leppäkangas, Michael Marthaler, Gerd Schön. Phase-dependent quasiparticle tunneling in Josephson junctions: Measuring the cos? term with a superconducting charge qubit,
Physical Review B, (08 2011): 60505. doi: 10.1103/PhysRevB.84.060505

08/01/2012 16.00 K. W. Murch, S. J. Weber, E. M. Levenson-Falk, R. Vijay, I. Siddiqi. 1/f noise of Josephson-junction-embedded microwave resonators at single photon energies and millikelvin temperatures,
Applied Physics Letters, (04 2012): 142601. doi: 10.1063/1.3700964

08/01/2012 15.00 Nicolas Vogt, Jared Cole, Michael Marthaler, Gerd Schön. Influence of two-level fluctuators on adiabatic passage techniques,
Physical Review B, (05 2012): 174515. doi: 10.1103/PhysRevB.85.174515

08/01/2012 11.00 S. Anton, C. Müller, J. Birenbaum, S. O'Kelley, A. Fefferman, D. Golubev, G. Hilton, H.-M. Cho, K. Irwin, F. Wellstood, Gerd Schön, A. Shnirman, John Clarke. Pure dephasing in flux qubits due to flux noise with spectral density scaling as 1/f^{?},
Physical Review B, (06 2012): 224505. doi: 10.1103/PhysRevB.85.224505

08/01/2012 12.00 Juha Leppäkangas, Michael Marthaler. Fragility of flux qubits against quasiparticle tunneling,
Physical Review B, (04 2012): 144503. doi: 10.1103/PhysRevB.85.144503

08/01/2012 14.00 Jan Jeske, Jared H Cole, Clemens Müller, Michael Marthaler, Gerd Schön. Dual-probe decoherence microscopy: probing pockets of coherence in a decohering environment,
New Journal of Physics, (02 2012): 23013. doi: 10.1088/1367-2630/14/2/023013

08/08/2013 17.00 S. M. Anton, C. D. Nugroho, J. S. Birenbaum, S. R. O'Kelley, V. Orlyanchik, A. F. Dove, G. A. Olson, Z. R. Yoscovits, J. N. Eckstein, D. J. Van Harlingen, John Clarke. Low-frequency critical current noise in Josephson junctions induced by temperature fluctuations,
Applied Physics Letters, (08 2012): 92601. doi: 10.1063/1.4749282

08/08/2013 24.00 C. D. Nugroho, V. Orlyanchik, D. J. Van Harlingen. Low frequency resistance and critical current fluctuations in Al-based Josephson junctions,
Applied Physics Letters, (04 2013): 142602. doi: 10.1063/1.4801521

08/08/2013 23.00 Clemens Müller, Alexander Shnirman, Martin Weides. T_{1}-echo sequence: Protecting the state of a qubit in the presence of coherent interaction,
Physical Review A, (09 2012): 32335. doi: 10.1103/PhysRevA.86.032335

08/08/2013 22.00 O. Yaakobi, L. Friedland, C. Macklin, I. Siddiqi. Parametric amplification in Josephson junction embedded transmission lines,
Physical Review B, (04 2013): 144301. doi: 10.1103/PhysRevB.87.144301

08/08/2013 21.00 K. W. Murch, E. Ginossar, S. J. Weber, R. Vijay, S. M. Girvin, I. Siddiqi. Quantum state sensitivity of an autoresonant superconducting circuit,
Physical Review B, (12 2012): 220503. doi: 10.1103/PhysRevB.86.220503

08/08/2013 20.00 K. W. Murch, S. J. Weber, K. M. Beck, E. Ginossar, I. Siddiqi. Reduction of the radiative decay of atomic coherence in squeezed vacuum,
Nature, (07 2013): 62. doi: 10.1038/nature12264

08/08/2013 19.00 I A B Sognnaes, J S Birenbaum, S R O'Kelley, C J Fourie, John Clarke, S M Anton. Mean square flux noise in SQUIDs and qubits: numerical calculations,
Superconductor Science and Technology, (07 2013): 75022. doi: 10.1088/0953-2048/26/7/075022

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Physical Review Letters, (04 2013): 147002. doi: 10.1103/PhysRevLett.110.147002

08/29/2011 1.00 J. Aumentado, K. W. Murch, L. Friedland, I. Siddiqi, R. Vijay, I. Barth, O. Naaman. Quantum fluctuations in the chirped pendulum,
Nature Physics, (12 2010): 105. doi: 10.1038/nphys1867

08/29/2011 9.00 J. Lisenfeld, C. Müller, J. Cole, P. Bushev, A. Lukashenko, A. Shnirman, A. Ustinov. Measuring the Temperature Dependence of Individual Two-Level Systems by Direct Coherent Control,
Physical Review Letters, (12 2010): 230504. doi: 10.1103/PhysRevLett.105.230504

08/29/2011 8.00 G J Grabovskij, P Bushev, J H Cole, C Müller, J Lisenfeld, A Lukashenko, A V Ustinov. Entangling microscopic defects via a macroscopic quantum shuttle,
New Journal of Physics, (06 2011): 63015. doi: 10.1088/1367-2630/13/6/063015

08/29/2011 7.00 J. H. Cole, A. Lukashenko, A. V. Ustinov, A. Shnirman, C. Mueller, P. Bushev, G. J. Grabovskij, J. Lisenfeld. Quantitative evaluation of defect-models in superconducting phase qubits,
Applied Physics Letters, (12 2010): 252501. doi: 10.1063/1.3529457

08/29/2011 6.00 C. Müller, J. Lisenfeld, J. Cole, A. Lukashenko, A. Shnirman, P. Bushev, A. Ustinov. Multiphoton spectroscopy of a hybrid quantum system,
Physical Review B, (10 2010): 134530. doi: 10.1103/PhysRevB.82.134530

08/29/2011 5.00 James N. Eckstein, Timothy J. McArdle, Paul B. Welander. Reduced leakage current in Josephson tunnel junctions with codeposited barriers,
Applied Physics Letters, (12 2010): 233510. doi: 10.1063/1.3518983

08/29/2011 4.00 M. H. Devoret, John Clarke, Archana Kamal. Noiseless non-reciprocity in a parametric active device,
Nature Physics, (01 2011): 311. doi: 10.1038/nphys1893

08/29/2011 3.00 Irfan Siddiqi. Superconducting qubits: poised for computing?,
Superconductor Science and Technology, (09 2011): 91002. doi: 10.1088/0953-2048/24/9/091002

08/29/2011 2.00 S. J. Weber, K. W. Murch, D. H. Slichter, R. Vijay, I. Siddiqi. Single crystal silicon capacitors with low microwave loss in the single photon regime,
Applied Physics Letters, (04 2011): 172510. doi: 10.1063/1.3583449

09/29/2014 25.00 Martin Gustafsson, Arsalan Pourkabirian, Göran Johansson, John Clarke, Per Delsing. Thermal properties of charge noise sources,
Physical Review B, (12 2013): 25410. doi: 10.1103/PhysRevB.88.245410

09/29/2014 26.00 John Clarke, Gerd Schön, Alexander Shnirman, Juan Atalaya. Flux $1/f?$ noise in two-dimensional Heisenberg spin glasses: Effects of weak anisotropic interactions,
Physical Review B, (07 2014): 14206. doi: 10.1103/PhysRevB.90.014206

TOTAL: **25**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>   <u>Paper</u>

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Number of Papers published in non peer-reviewed journals:

(c) Presentations

Coherence Properties of a Capacitively-Shunted Flux Qubit, Jeffrey Birenbaum, A. Sears, C. D. Nugroho, T. Gudmundsen, P. Welander, J. L. Yoder, A. Kamal, S. Gustavsson, A. J. Kerman, W. D. Oliver and John Clarke, APS March Meeting, Denver, CO, 3 March 2014.

Design and Measurement of Improved Capacitively Shunted Flux Qubits, Adam Sears, Jeffrey Birenbaum, David Hover, T. Gudmundsen, A. J. Kerman, P. Welander, J.L. Yoder, A. Kamal, S. Gustavsson, Xiaoyue Jin, John Clarke and W. D. Oliver, APS March Meeting, Denver, CO, 3 March 2014.

Low-Power Dispersive Measurements of High-Coherence Flux Qubits, David Hover, Adam Sears, T. Gudmundsen, A. J. Kerman, P. Welander, J.L. Yoder, A. Kamal, S. Gustavsson, Xiaoyue Jin, Jeffrey Birenbaum, John Clarke and W. D. Oliver, APS March Meeting, Denver, CO, 5 March 2014.

Josephson traveling-wave parametric amplifier for superconducting qubit readout, Chris Macklin, D.H. Slichter, O. Yaakobi, L. Friedland, V. Bolkhovsky, D.A. Braje, G. Fitch , W.D. Oliver, I. Siddiqi. APS March Meeting, Denver, CO, March 5, 2014.

Improved Capacitively-Shunted Flux Qubits, J. Birenbaum, X. Jin, A. Kamal, S. Gustavsson, F. Yan, T. Gudmundsen, D. Hover, A. Sears, J. Yoder, A. J. Kerman, T. Orlando, W. D. Oliver, and J. Clarke, Applied Superconductivity Conference, Charlotte, NC, August 12, 2014.

Number of Presentations: 5.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>   <u>Paper</u>

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Received   Paper

   TOTAL:

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(d) Manuscripts

Received   Paper

09/29/2014 27.00 Kevin O'Brien, Chris Macklin , Irfan Siddiqi, Xiang Zhang. Resonantly phase-matched Josephson junction
                  traveling wave parametric amplifier,
                  Physical Review Letters (accepted) (09 2014)

   TOTAL: **1**

Number of Manuscripts:

Books

Received   Book

   TOTAL:

TOTAL:

Patents Submitted

Josephson junction transmission line parametric amplifier" by Chris Macklin, Daniel Slichter, Oded Yaakobi, Lazar Friedland, and Irfan Siddiqi. Filed January 28, 2014

Patents Awarded

Awards

None

Graduate Students

NAME	PERCENT SUPPORTED	Discipline
Steve Anton	0.49	
Jeffrey Birenbaum	0.49	
Chris Nugroho	0.49	
FTE Equivalent:	**1.47**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT SUPPORTED
None	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT SUPPORTED	National Academy Member
John Clarke	0.08	Yes
Irfan Siddiqi	0.08	
FTE Equivalent:	**0.16**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT SUPPORTED	Discipline
None	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:······ 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:····· 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):······ 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:····· 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
None
Total Number: 1

Names of personnel receiving PHDs

NAME
Steve Anton
Total Number: 1

Names of other research staff

NAME	PERCENT SUPPORTED
None	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

UCB (Clarke)

Flux Qubits

Starting in September, 2013, in collaboration with MIT-LL, we switched focus from the traditional flux qubit to the capacitively-shunted flux qubit. This change was motivated by several limitations of the flux qubit, the most dominant of which are the sensitivity to flux noise —responsible for the rapid decay of T2 away from degeneracy—and the sensitivity to stray capacitances—believed to limit T1 and reproducibility. The addition of a capacitive shunt across the small junction of a traditional flux qubit, with a value much greater than any stray capacitance and the self-capacitance of the junction itself, ensures that virtually all the electric field energy is stored in the capacitive shunt, which we can design to be high-Q. The C-shunt flux qubit also allows us to explore a parameter range where the critical current density jc is significantly lower than typical values used in a traditional flux qubit. The result is a qubit with greatly decreased sensitivity to flux noise, with the matrix element smaller by a factor of 10, yielding a 100-fold decrease in the pure dephasing rate.

Qubits from a total of more than 20 fabrication runs were measured this year at UCB alone; numerous other devices were measured at MIT and MIT-LL. UCB and MIT-LL initially followed very different paths with regard to C-shunt design to cover a large fraction of the available parameter space effectively. UCB initially pursued qubits with four junctions, all four of which were shunted in proportion to their critical currents, coupled to a lumped element resonator. Comparing our results with those from MIT-LL it became evident that shunting all four junctions was unnecessary and only served to make the qubit physically larger. This was not immediately apparent a priori as shunting all junctions preserves symmetry in the Hamiltonian. Additionally, the fourth junction was dropped with no loss in performance, making fabrication somewhat simpler. Early iterations of the C-shunt devices suffered from low quality films, but once high quality, MBE-grown films were produced at MIT-LL we started to achieve significant improvements. Initial measurements on devices with high quality films—single shunts, four junctions at the time, lumped element resonator—yielded T1 values off-degeneracy of up to 90 ¿s. This came at a cost of reduced qubit frequency (0.5-1.5 GHz) and reduced T1 at degeneracy (0.5-4 ¿s). With the data acquired from these devices we shifted to a lower jc and larger capacitance. Additionally, we changed the shunt geometry from an initial highly-interdigitated capacitor to parallel bars for the final design. Qubits of the coplanar waveguide (CPW) design from MIT-LL with these changes produced T1 times at degeneracy of up to 30 ¿s as measured at UCB, a factor of 5 improvement over traditional flux qubits. T2 values lagged behind at UCB, measuring only ~5-10 ¿s on these devices vs. 15-25 ¿s measured at MIT/MIT-LL. We are actively seeking the source of the discrepancy and have had some moderate success by changing the grounding scheme of the measurement setup, but to date we have found no 'smoking gun'.

UCB also developed a bridgeless junction technique this year. This method forms junctions using a mask consisting of intersecting perpendicular lines. The patterned mask is robust against aggressive cleaning and, more importantly, produces junctions with high dimensional accuracy. UCB demonstrated that, without any process optimization, junctions could be produced at the (150 nm)2 size to better than 5% accuracy across millimeter length scales. We note that this corresponds to less than 4 nm error on the length and width of the junctions. With optimization we believe we could produces junctions with sizes accurate to 1-2 nm on each side. Devices of the MIT-LL design fabricated using these bridgeless junctions on 100 nm MBE-grown Al yielded T1 times up to 15-20 ¿s, comparable to results from devices with traditional bridge-type junctions. UCB believes these bridgeless junctions are an important development for the C-shunt qubit as they allow for better frequency control than traditional bridge-type junctions. This precision will be essential as devices are scaled into multi-qubit architectures, where accurate frequency control is essential.

Flux Noise

It is widely accepted that magnetic flux noise, which limits the value of T2 in flux qubits, arises from the reversal of spins on the upper and lower surfaces of the superconducting films. Flux noise has a spectral density that scales as 1/f¿, where ¿ is of the order of unity. Measurements on dc SQUIDs at UCB and elsewhere have shown that this noise exists down to frequencies of 10-4 Hz, with no reason to believe that the noise does not continue down to much lower frequency.

A persistent issue with the surface spin model is that there is no obvious mechanism by which a given spin retains its orientation for times as long as1/ (10-4 Hz) ~ 3 hours. This problem has been tackled effectively by the KIT theory group. They investigated the dynamics of a two-dimensional ensemble of randomly distributed classical Heisenberg spins with isotropic RKKY coupling via the electron bath in the metal and weaker anisotropic dipole-dipole coupling between the spins. Their numerical simulations show that Ising type fluctuators, which arise from spin clustering close to a spin glass critical behavior with zero critical temperature, give rise to 1/f¿¿noise. The value of ¿(T) ¿ 1 increases towards unity as the temperature is lowered, in agreement with experimental observations. The distribution of time constants required to produce 1/f¿ noise arises from a distribution in the size of the spin clusters.

UCB (Siddiqi)

Traveling wave parametric amplifier

Remarkable progress on the development of the Traveling Wave Parametric Amplifier (TWPA) has occurred over the last program year. We started a new collaboration with Kevin O'Brien in the group of Prof. Xiang Zhang in the UC Berkeley Department of Mechanical Engineering, specialists in engineering optical metamaterials. Through this collaboration we developed the technique of "resonant phase matching", an entirely new technique for phase matching a nonlinear traveling wave process unique to superconducting microwave metamaterials like the TWPA. By adding a series of linear shunt resonators to the nonlinear Josephson junction transmission line comprising the TWPA, we have corrected the intrinsic phase mismatch between the pump and signal in the nonlinear regime relevant to amplifier operation. With this phase mismatch corrected, the gain provided by the TWPA is improved by over an order of magnitude to 20 dB or higher, with a significant improvement in bandwidth as well - over 3 GHz full-width at 20 dB gain. We have published these theoretical results in a manuscript in Physical Review Letters.

Technology Transfer

None

Final Report

John Clarke and Irfan Siddiqi

We present an overview of our research on the following topics: Flux 1/f Noise, Flux Qubits, Single Crystal Silicon Capacitors, 1/f Frequency Noise in Josephson-junction-embedded microwave resonators, Dielectric Loss in Josephson Junctions, Quantum Bath Engineering and Traveling Wave Parametric Amplifiers.

Flux 1/f Noise (Clarke)

Magnetic flux 1/f noise is a universal phenomenon in superconducting films that increases the low frequency noise of Superconducting Quantum Interference Devices (SQUIDs) and causes decoherence in certain kinds of superconducting qubits, notably flux qubits. The noise spectral density scales as $1/f^{\alpha}$, where α is typically in the range 0.4 to 0.9. The noise amplitude at 1 Hz is typically on the order of $1\mu\Phi_0 Hz^{-1/2}$.

To investigate the materials, geometry and temperature dependence of flux 1/f noise we made detailed studies of a large number of Nb-based SQUIDs, many of them fabricated by our collaborators at UIUC and NIST, Boulder. Our measurement system is capable of independently measuring the 1/f noise in any one of up to six SQUIDs, usually fabricated simultaneously on a single chip, in a single cool-down of our dilution refrigerator. The noise is measured by connecting each SQUID in turn to the input coil of the measuring SQUID. The absolute value of the noise is obtained by a careful calibration of the relevant circuit parameters, and validated by measurements of Nyquist noise in a resistor. We characterize each acquired noise power spectral density S(f) by its fitted noise power at 1 Hz and its slope (alpha), and find that both quantities vary in a systematic way.

We acquired detailed data sets on four chips, each with five SQUIDs, where the geometries were systematically varied and measurements were taken at numerous temperatures. The general findings are: (1) The noise increases slowly as the temperature is lowered. (2) At a given temperature, for a set of SQUIDs fabricated simultaneously, the noise increases with the ratio R/W, where R is the radius of the SQUID loop and W is the width of the loop. (3) The slope of the power spectrum, α, increases steadily as the temperature is lowered, from about 0.4 at 4 K to 0.9 at 0.1 K. (4) Remarkably, for each SQUID the spectra "pivot" about a fixed frequency as the temperature is varied. This remarkable effect has major implications for the hypothesis that surface spins interact to form clusters. (5) In collaboration with NIST, Boulder, we investigated the effect of depositing SiNx on the SQUID washer following a surface cleaning of the Nb film. On the average, this treatment reduced the noise power at 1 Hz by a factor of 2.

The notion that surface spins interact to form clusters led to a detailed simulation by the Karlsruhe group. They studied the dynamics of a two-dimensional ensemble of randomly distributed Heisenberg spins with isotropic RKKY interaction via the electron spins in the metal and weaker anisotropic dipole-dipole couplings. They simulated the equations of motion, and

found that the spins form clusters of random sizes that produce $1/f^\alpha$ noise via spin reversals with a broad range of time constants. The temperature dependent exponent $\alpha(T)$ approaches unity as the temperature is lowered, in agreement with experimental observations.

It is generally accepted that flux $1/f$ noise is produced by the random reversal of spins on the surfaces of the superconducting films. To improve our understanding of the way that the spins couple flux into the superconducting loop, we developed a numerical model for computing the mean square flux noise of SQUIDs and qubits. Unlike previous methods, ours is computationally efficient, accurate, and valid for arbitrary geometries. In addition, our method computes contributions from spins located on the edges of the thin-film superconductor, a contribution for which previous methods are unable to account. We studied square washers in which we varied the dimensions over many orders of magnitude and found edge spins to be important— even dominant—in qubit-like geometries. We also compared our results to a well-known analytic result and found significant discrepancies, which we traced back to approximations used in its derivation.

Flux Qubits (Clarke)

The traditional flux qubit consists of three Josephson junctions—two of them with identical critical currents and the third with a smaller critical current—connected in series on a superconducting loop. Although the flux qubit was one of the earliest superconducting qubits, its relaxation time T_1 and decoherence time T_2 remained very low, typically a few microseconds, with the exception of a solitary "hero" device which attained $T_1 = 12$ μs and $T_2 = 23$ μs at the degeneracy point.

In an attempt to increase these times, we modified the geometry of the flux qubit by adding a thin film, shunt capacitor across the smallest junction. In collaboration with MIT and MIT-LL, we fabricated and characterized a large number of flux qubits with a wide range of designs. The expectation was that this would enable us to redesign the qubit parameters to have two major advantages over the conventional flux qubit: (1) Since the shunt capacitance is much greater than the small junction capacitance and associated stray capacitances, most of the electromagnetic energy would be stored in the shunt capacitor. Since the external shunt geometry can be designed independently of the qubit geometry, the Q can be significantly enhanced, thereby increasing T_1. (2) The flexibility in the design allows us to reduce the magnitude of the supercurrent I_q circulating in the qubit loop substantially, thereby reducing the qubit coupling to flux noise. Since T_2 sales inversely as I_q^2, this approach offers an enhancement of T_2 by one to two orders of magnitude away from degeneracy. A further advance, implemented at MIT-LL, was to improve the quality of the thin Al films, for example, by annealing the sapphire substrates and growing some of the films with MBE.

Qubits from more than 20 fabrication runs were measured at UCB alone; numerous other devices were measured at MIT and MIT-LL. UCB and MIT-LL initially followed very different paths with regard to C-shunt design to cover a large fraction of the available parameter space effectively. At UCB, we initially pursued qubits with four junctions, all four of which were shunted in proportion to their critical currents, coupled to a lumped element resonator. Comparing our results with those from MIT-LL it became evident that shunting all four junctions

did not offer any discernible improvements in T_1 or T_2, and served only to make the qubit physically larger. This was not apparent *a priori* as shunting all junctions preserves symmetry in the Hamiltonian. Additionally, the fourth junction was dropped with no loss in performance, making fabrication somewhat simpler. Early iterations of the C-shunt devices suffered from low quality films, but once high quality, MBE-grown films were produced at MIT-LL we started to achieve significant improvements. Initial measurements at UCB on devices with high quality films, a single shunt capacitor and a lumped element resonator yielded T_1 values off-degeneracy of up to 90 μs. This came at a cost of reduced qubit frequency (0.5-1.5 GHz) and reduced T_1 at degeneracy (0.5-4 μs). With the data acquired from these devices we shifted to a lower I_q and larger capacitance. Additionally, we changed the shunt geometry from an initial highly-interdigitated capacitor to parallel bars for the final design. Qubits of the coplanar waveguide (CPW) design from MIT-LL with these changes produced T_1 times at degeneracy of up to 30 μs as measured at UCB, a factor of at least 5 improvement over traditional flux qubits. Our best T_2 values at UCB were ~ 10 μs.

The best results measured at MIT and MIT-LL with junctions fabricated at UCB were a maximum T_1 at degeneracy of 55 μs, with values for the best design in the range $35 - 55$ μs for qubit frequencies Δ/h around 5 GHz. The corresponding values of decoherence times obtained with an echo, T_{echo}, varied from 30 to 40 μs.

It is believed that this improvement results from the reduction in the electric fields at the edges of the junction and C-shunt because much of the stored energy has been transferred to the C-shunt and because the dimensions of the C-shunt are much larger than those of the junctions. In turn, these weaker electric fields suffer lower loss in the nearby environment, for example, the substrate. The resulting higher quality factor Q increases T_1. It is believed that the increase in T_1 may also be due in part to the use of high quality Al films for the qubit and C-shunt, which may improve the quality of the film-substrate interface. At degeneracy, the increase in T_1 leads to an increase in T_2. The decrease in the circulating supercurrents in the qubit loop, and thus the reduced coupling of the qubit to flux 1/f noise, results in an increase in T_2 away from degeneracy.

Interestingly, for a qubit with a splitting frequency below 1 GHz, the value of T_1 appears to be limited by high frequency flux 1/f noise. This raises the extremely important question of whether T_1 in conventional flux qubits is limited by flux 1/f noise, and that the substantial increase in T_1 we have achieved is due in part to the reduction in the qubit coupling to flux noise because of the reduced circulating current.

Finally, a singular advantage of our C-shunt flux qubits is their relatively high anharmonicity: typically $A = (f_{12} - f_{01})/f_{01}) \approx 0.1 - 0.2$. For the transmon, another superconducting qubit with high values of T_1 and T_2, by comparison $A \approx -0.05$.

At UCB we also developed a bridgeless junction technique. This method forms junctions using a mask consisting of intersecting perpendicular lines. The patterned mask is robust against aggressive cleaning and, more importantly, produces junctions with high dimensional accuracy. We demonstrated that, without any process optimization, junctions could be produced at the (150 nm)^2 size to better than 5% accuracy across millimeter length scales. We note that this corresponds to less than a 4-nm error on the length and width of the junctions. With optimization we believe we could produces junctions with sizes accurate to 1-2 nm on each side. Devices of

the MIT-LL design fabricated using these bridgeless junctions on 100-nm MBE-grown Al yielded T_1 values up to 15-20 μs, comparable to results from devices with traditional bridge-type junctions. We believe these bridgeless junctions are an important development for the C-shunt qubit as they allow for better critical current control, and thus better frequency control than traditional bridge-type junctions. This precision will be essential as devices are scaled into multi-qubit architectures, where accurate frequency control is essential.

Single Crystal Silicon Capacitors

Superconducting circuits such as quantum bits, inductance based photon detectors, and linear resonators require low loss reactive microwave components to achieve a high internal quality factor Q_i. At frequencies below the energy gap, superconducting metallic wires function as high quality inductors whose remnant loss is presumably due only to surface and interface defects and/or the presence of non-equilibrium quasiparticles. Capacitive elements, particularly structures involving amorphous dielectric layers, typically have significantly greater loss. For planar lumped-element resonators and qubits the highest Q_i values are typically achieved using the geometric capacitance of single-layer micro-fabricated superconducting structures such as interdigitated capacitors, on single crystal silicon or sapphire substrates. Such circuits achieve Q_i values of several hundred thousand with an average resonator population of one photon, but it is difficult to realize capacitances larger than about 1 pF in this geometry. Higher capacitances can be obtained in a parallel plate geometry using either deposited amorphous dielectrics such as SiO_2, a-Si:H, or SiN_x or vacuum gaps. However, deposited dielectrics exhibit significant loss in the low temperature, low power regime due to the presence of two-level state (TLS) defects, limiting their utility for quantum circuits. Current vacuum gap capacitors suffer from loss from necessary support structures and surface oxides, and are on par with the best deposited dielectrics, with a loss tangent $\tan \delta_i = 1/Q_i = 2.2\text{-}3\times10^{-5}$ in the 4-8 GHz band. Crystalline dielectrics, such as silicon can exhibit low intrinsic loss and have been used in the fabrication of superconducting bolometers using a wafer bonding process.

We have fabricated superconducting microwave resonators in a lumped element geometry using single crystal silicon dielectric parallel plate capacitors with C > 2 pF. Aluminum devices with resonant frequencies between 4.0 and 6.5 GHz exhibited an average internal quality factor Q_i of 2×10^5 in the single photon excitation regime at T = 20 mK. Attributing the observed loss to the capacitive element, our measurements place and upper bound on the loss tangent of the silicon dielectric layer of $\tan \delta_i = 5 \times 10^{-6}$. This level of loss is an order of magnitude lower than is currently observed in structures incorporating amorphous dielectric materials, thus making single crystal silicon capacitors an attractive, robust route for realizing long-lived quantum circuits.

Our results indicate that single crystal silicon capacitors are very promising for use in high quality factor superconducting circuits which require > pF of shunting capacitance, such as the phase qubit. In fact, the group of Robert McDermott has recently used single crystal silicon capacitors for realize the longest-lived phase qubits reported to date, with T_1 times of several

microseconds. Furthermore, incorporating these elements into classical non-linear resonators consisting of a capacitively shunted Josephson junction has allowed us to make precise characterization of the high frequency loss and 1/f noise in Josephson junctions.

1/f Frequency Noise in Josephson-junction-embedded microwave resonators

We have performed measurements of 1/f frequency noise in both linear and Josephson-junction-embedded superconducting aluminum resonators in the low power, low temperature regime—typical operating conditions for superconducting qubits. The junction-embedded resonators consist of a shadow evaporated $Al/AlO_x/Al$ Josephson junctions with critical current $I_0 \approx 1$ μA and areas up to 0.44 μm^2 shunted by single crystal silicon capacitors of capacitance C = 1.1 pF. The addition of the Josephson junction does not result in additional frequency noise, thereby placing an upper limit for fractional critical current fluctuations of 1×10^{-8} (1/√Hz) at 1 Hz for sub-micron, shadow evaporated junctions. These values imply a minimum dephasing time for a superconducting qubit due to critical current noise of $40 - 1400$ μs depending on qubit architecture. Occasionally, at temperatures above 50 mK, we observe the activation of individual fluctuators which increase the level of noise significantly and exhibit Lorentzian spectra.

Dielectric Loss in Josephson Junctions

We have performed loss measurements of 4-8 GHz superconducting resonant circuits embedded with Josephson junctions. The junction behaves as a nonlinear inductor, which is connected in series with a stray linear inductance and shunted by a capacitor. The junction also has loss, modeled as a resistor, and a self capacitance. Capacitive energy is divided between the junction capacitance, C_j, and the shunting capacitance, C_s, while inductive energy is divided between the Josephson inductance, L_j, and the stray inductance, L_s. Thus, a large area junction with a small shunting capacitance is required to observe loss in the junction dielectric over other sources of resonator loss. Likewise, a high inductive participation ratio $p_j = L_j /(L_s + L_j)$ is required to observe loss due to quasiparticle tunneling.

We have characterized junction loss in two different ways– by measuring the quality factor of junction embedded quasi-lumped-element resonators with high p_j and by measuring the relaxation time T_1 of transmon qubits dispersively coupled to 3D cavities. In both geometries, we measure shadow evaporated aluminum junctions with a wide range of critical currents and areas. We observe no dependence of loss on junction size, for areas as large as 0.44 μm^2, indicating that our resonators are not limited by dielectric loss in the junction capacitance. However, junction loss is highly dependent on the embedding geometry, which suggests the influence of non-equilibrium quasiparticles.

Quantum Bath Engineering

In practice, quantum systems are never completely isolated, but instead interact with degrees of freedom in the surrounding environment, eventually leading to decoherence of some states of the system. Precision measurement techniques such as nuclear magnetic resonance and interferometry, as well as envisioned quantum schemes for computation, simulation, and data encryption, rely on the ability to prepare and preserve delicate quantum superpositions and entanglement. The conventional route to long-lived quantum coherence involves minimizing coupling to a dissipative bath. Paradoxically, it is possible to instead engineer specific couplings to a quantum environment that allow dissipation to actually preserve coherence. We have demonstrated such quantum bath engineering for a superconducting qubit coupled to a microwave frequency cavity. By tailoring the spectrum of microwave photon shot noise in the cavity, we create a dissipative environment that autonomously relaxes the qubit to an arbitrarily specified coherent superposition of the ground and excited states. In the presence of background thermal excitations, this mechanism increases the state purity and effectively cools the dressed qubit state to a low temperature. Cavity-assisted cooling of the qubit can be tailored to produce any arbitrary superposition of ground and excited states on demand with high fidelity.

Traveling Wave Parametric Amplifiers

Currently, most state-of-the-art superconducting qubit experiments rely on resonator-based parametric amplifiers for high efficiency quantum-non-demolition readout. The resonant structure places limits on amplifier bandwidth and dynamic range, which are important performance metrics for fast multiplexed qubit readout. To overcome the fundamental limitations of resonator-based paramps, we have developed non-resonant traveling wave parametric amplifiers (TWPAs). Traveling wave parametric amplifier. Remarkable progress on the development of the Traveling Wave Parametric Amplifier (TWPA) has occurred over the last program year. We started a new collaboration with Kevin O'Brien in the group of Prof. Xiang Zhang in the UC Berkeley Dept. of Mechanical Engineering, specialists in engineering optical metamaterials. Through this collaboration we developed the technique of "resonant phase matching", an entirely new technique for phase matching a nonlinear traveling wave process unique to superconducting microwave metamaterials like the TWPA. By adding a series of linear shunt resonators to the nonlinear Josephson junction transmission line comprising the TWPA, we have corrected the intrinsic phase mismatch between the pump and signal in the nonlinear regime relevant to amplifier operation. With this phase mismatch corrected, the gain provided by the TWPA is improved by over an order of magnitude to 20 dB or higher, with a significant improvement in bandwidth as well - over 3 GHz full-width at 20 dB gain. We have published these theoretical results in Physical Review Letters.